

Study of the Properties of New SPM Detectors

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ABSTRACT

The operation and performance of multi-pixel, Geiger-mode APD structures referred to as Silicon Photomultiplier (SPM) are reported. The SPM is a solid state device that has emerged over the last decade as a promising alternative to vacuum PMTs. This is due to their comparable performance in addition to their lower bias operation and power consumption, insensitivity to magnetic fields and ambient light, smaller size and ruggedness. Applications for these detectors are numerous and include life sciences, nuclear medicine, particle physics, microscopy and general instrumentation. With SPM devices, many geometrical and device parameters can be adjusted to optimize their performance for a particular application. In this paper, Monte Carlo simulations and experimental results for 1mm^2 SPM structures are reported. In addition, trade-offs involved in optimizing the SPM in terms of the number and size of pixels for a given light intensity, and its affect on the dynamic range are discussed.

Keywords: Photodiode, avalanche, Geiger-mode, silicon photomultiplier, PMT

1. INTRODUCTION

The ability to detect photons and have accurate information on the magnitude of the flux, its arrival time and duration, is of critical importance to many applications. These range from biology, medicine, communications, environmental monitoring, particle and space physics to general instrumentation. Each application enforces a different set of requirements on the photodetector element, resulting in the many custom detector choices available on the market today. These range from solid-state PIN and APD devices to vacuum based photomultiplier (PMT) solutions [1]. In recent times, the dominance of PMT's has been challenged by the advance of silicon technologies and the development of novel detector devices, see for example single photon counter applications [2]. One in particular, termed here the Silicon Photomultiplier (SPM), has emerged as a direct competitor to the traditional PMT technology.

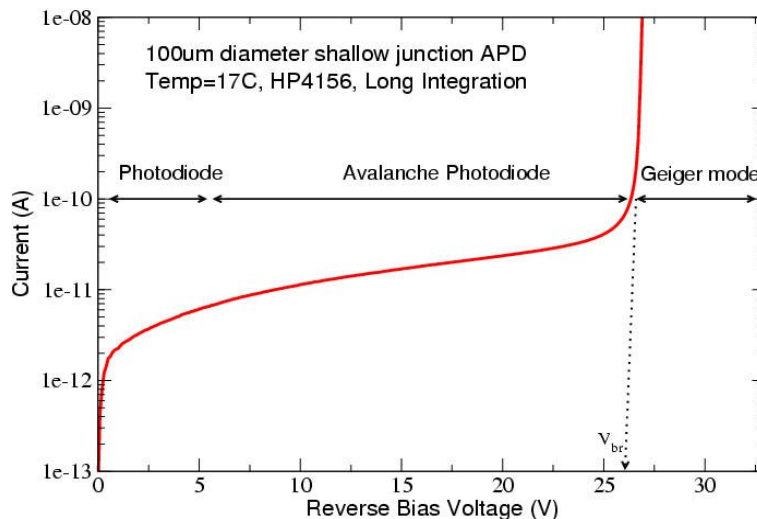


Fig 1. Different operation modes for solid state Silicon detectors showing: Photodiode (linear, no gain), Avalanche (linear, gain of 10-200) and Geiger mode (photon counting, single photon = current pulse out)

Compared to existing PIN and APD diodes, SPM devices have many inherent advantages. PIN structures are limited due to the fact that the signal generated is very small, resulting in a poor signal-to-noise ratio. In addition, the drift speed of the carriers is low for the typical biases applied and so the timing of these devices is poor. The APD is an advance in the concept of the PIN structure and typically has faster timing capability and intrinsic gain, see Figure 1. However, the intrinsic gain is limited to low values (typ. 50-100) for stable operation, due to an exponential dependence of the gain on the bias voltage. Despite this limitation, APDs are in some cases (e.g. small animal PET and high energy physics) being used as an alternative to PMTs due to their very high quantum efficiency (80% max), their compactness, ruggedness and insensitivity to magnetic fields. However, the limited gain, (implying a need for sensitive, low noise electronics) and the additional need for beveled edges (keeping fabrication costs high) have meant that the general uptake of these devices, as a general replacement for the PMT, has been slow.

By contrast, the SPM is a novel, high-gain APD structure that has a performance comparable to PMT devices and overcomes the limitations of traditional PIN/APD diodes. SPM devices were first developed in Russia in the mid-1980s after the study of the stationary avalanche multiplication of photocurrent in metal-conducting dielectric-semiconductor structures. Referred to in the literature as SiPM, MRS APD or SSPM, the first actual photodetectors based upon this structure were produced in 1989. At the beginning of the 90s the first physics test results started to appear with continuing sensor development at MEPHI [3,4] and CPTA (Centre for Perspective Technologies) [5,6] in Russia. Over the last 10 years the amount of literature on the study and development of these devices has increased [7,8]. For some years now they have been studied as one of the detectors for the ILC project at DESY [9] and production of large prototypes based upon the SPM are now being constructed. There is also now work on applying them to the fields of Positron Emission Tomography (PET) by replacing PMT's detectors [10]. Compared with PMT's the technology is attractive in offering a low bias voltage, high gain, small form factor product that is not sensitive to magnetics or ambient light. This paper reviews SPM technology and highlights the experimental and theoretical device performance that makes them increasingly attractive for many applications.

1.1 SPM structure and fabrication

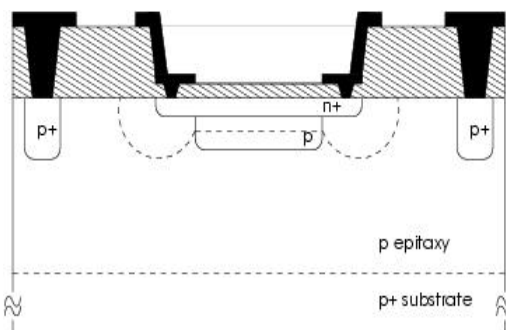


Fig. 2 Shallow junction Geiger-mode APD diodes which represents a single pixel of the SPM device structure.

At the core of the SPM device is an array of shallow junction avalanche photodiodes (APD) operated in Geiger mode [11]. The fabrication of Geiger-mode APDs (GAPD) is based on shallow silicon pn junction that makes them ideally suited for detection at short wavelengths. The schematic of a shallow junction GAPD detector is shown in Figure 2. For this work GAPDs were manufactured on epitaxially grown p-type bulk silicon using a conventional 1.5um CMOS process. The p layer, which defines the active area and the breakdown voltage, was ion implanted, while the n+ cathode was diffused to limit junction damage, increase defect gettering and decrease the dark count of the APDs. The n+ cathode overlaps the p layer to form a virtual guard ring that is necessary to prevent premature edge breakdown allowing above breakdown operation of the active area. The p+ implants at the edges of the structure form the anode contact and allow a planar structure which facilitates on wafer probing and is ideally suited for future flip-chip bonding into hybrid integrated systems. The structure in Figure 2 can be used over a wide range of operational modes allowing detection of photons from ambient light to single photon levels depending on the reverse bias applied and the readout and control circuitry used.

Geiger mode operation is achieved by biasing the diode above breakdown. At these bias levels the electric field at the junction is so high that a single carrier generated in the depletion region causes an avalanche where the whole diode goes

into breakdown and causes large current flow. Such a breakdown is referred to as a Geiger breakdown. In this 'on' state, the diode will continue to generate current, as the avalanche is self-perpetuating, until it is quenched in some way to turn it back to its 'off' or sensitive state. This quenching can be most easily achieved with a large series resistance that limits the current and provides feedback to lower the voltage and turn off the avalanche. Due to the sensitivity to each single electron produced in the active volume, and the corresponding large gain produced in this 'Geiger mode', such devices are sensitive to single photons. The current flowing is fixed regardless of the initial number of electrons that caused the breakdown, and can therefore be thought of as a logic signal. Therefore, such a GAPD is ideal as a single photon counting device. However, due to its binary nature, it is in no way a replacement for conventional PMT, which provides high gain, proportional information on the magnitude of the incoming photon flux.

A novel way to extend the concept of the GAPD is to provide an output signal proportional to the input photon flux. The SPM structure referred to in this paper is based on MxN pixel array of GAPD diodes that individually act as photon counters, see Figure 3. In Geiger mode the individual APD diodes are biased beyond electrical breakdown and the generated carriers acquire sufficient energy to result in a self-sustaining avalanche current flow. The current flow is limited by individual quench resistors, which turns off the breakdown and resets the diode. When all of the outputs are multiplexed together, the total device behaves like a proportional, 'analogue' device for photon fluxes. When a photon flux is incident upon the surface of this GAPD matrix, the number of pixels activated, and hence the size of the output current, is directly proportional to the number of incident photons. The SPM output is proportional and linear for $N_{\text{photoelectrons}} < N_{\text{cells}}$. The multi-cell structure essentially converts a binary device into an analogue device capable of measuring photon flux.

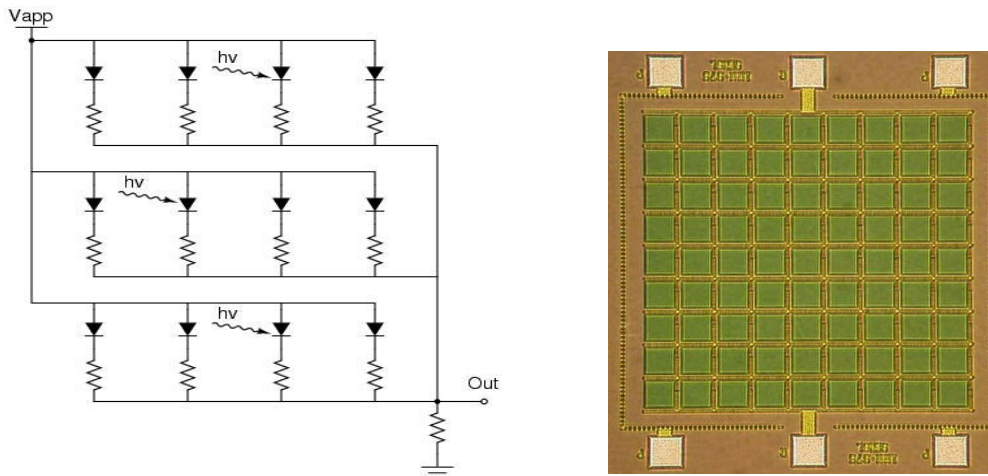


Fig. 3 left, SPM structure showing array of Geiger mode APD diodes with individual quench resistors connected in parallel, right, SensL's fabricated SPM consisting of 10 x 10 pixels array.

In addition to this feature, the novel structure yields other performance benefits. The gain is inherently high, as it is in normal GAPDs. In addition, the noise contribution of the device is minimal. The primary source of the leakage, or dark current is the thermal generation of carriers in the active volume. In the SPM, any electron generated in any of the cells will initiate a Geiger avalanche and give an output signal equal to 1 'photon'. In general, the rate of the generation of the thermal carriers is sufficiently low, that the probability of two cells firing simultaneously in such a way is very small. Therefore, the noise of this device is at the single photon level and can be characterized by a certain frequency. Setting a threshold just above the single photon level will eliminate virtually all noise. Other parameters, including the timing and quantum efficiency also turn out to be favorable when compared to the PMT. These performance aspects are in addition to the other practical benefits of a solid-state detector, such as compact and rugged packages, insensitivity to magnetic fields and typically low working bias voltages. The combination of these aspects leads to a very compelling device that could potentially replace the PMT in a wide range of applications.

2. RESULTS & DISCUSSION

The characterization of SPM structures is carried out at wafer and package level where parameters such as IV, dark counts, timing, gain and quantum efficiency are tested. Results for different parameters measured at room temperature for a 1mm^2 SPM cell are presented here. In addition, a Monte Carlo model has been developed which investigates SPM cell response for different optical input signals and geometrical parameters for optimal performance.

2.1 I-V, dark counts

On-wafer breakdown voltages and leakage current measurements were taken at room temperature on a range of SPM cells using a temperature controlled probe station. To date, the work on dark count in SensL's photodiodes showing it is mostly limited to defects in the junction which are currently being minimized[12]. Breakdown voltages for SPM cells were typically 50V with leakage currents ranging from 50pA to 1nA, see Figure 4. The dark count rate for the SPM cell can be measured from the rate displayed on the oscilloscope, with a threshold set just above the noise. The maximum dark rate is calculated as 1.8MHz for a 1mm^2 cell device measured at room temperature.

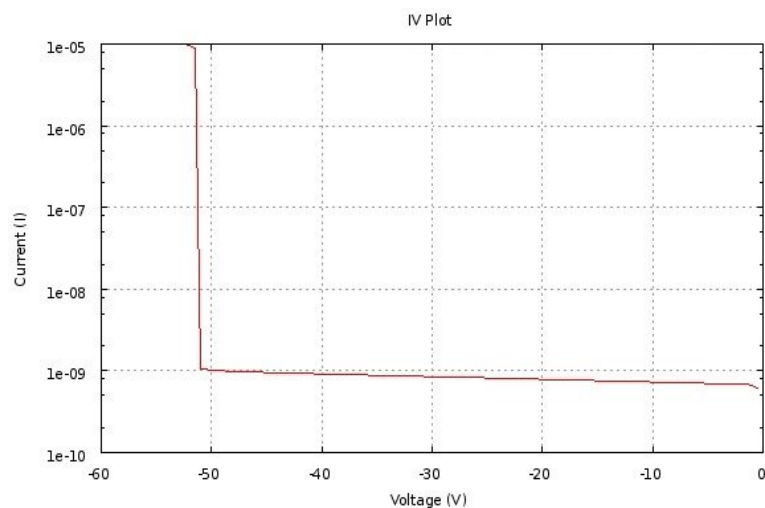


Fig. 4 Typical I-V plot of 1mm^2 SPM cell (pixel size 20 microns).

2.2 SPM signal pulse structure

The operation of the SPM cell can be further understood by observing SPM output pulses. The SPM output is connected to an oscilloscope via a preamp circuit with variable gain ranging from 10-100. Figure 5(a), shows a single dark count observed without light impinging on the detector and is equivalent to the signal produced from a single photoelectron. These dark counts generated due to thermal events are considered as noise. The pulses demonstrate the good response of the SPM device with fast rise ($<1.5\text{ns}$) and recovery ($\sim 10\text{ns}$) times. The output when a pulsed LED source illuminates the SPM device is shown in Figure 5(b). For reference, the LED trigger signal is shown on the top trace. The SPM response (bottom trace) to this signal input is clearly observed with minimal noise. In this example, the LED signal input ($<2\text{mW}/\text{cm}^2$ @ 650nm , $V_{\text{bias}}(\text{LED}) = 3.3\text{V}$) results in a large SPM output signal. The noise or dark counts are barely visible due to the high S/N ratio.

Reducing the light intensity ($<15\text{nW}/\text{cm}$) to the detector using a fibre pigtailed assembly, the pulse structure corresponding to a light level of the order of a few tens of photons is observed on the SPM output, see Figure 5(c). The fast response of the SPM results in the observed pulse structure, which corresponds to approx. 10 photons detected. In this case, the dark counts are visible due to the low light level conditions.

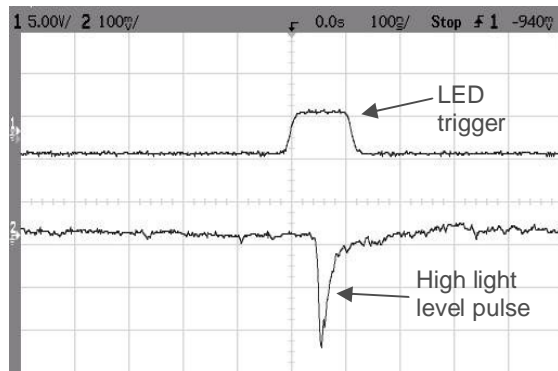
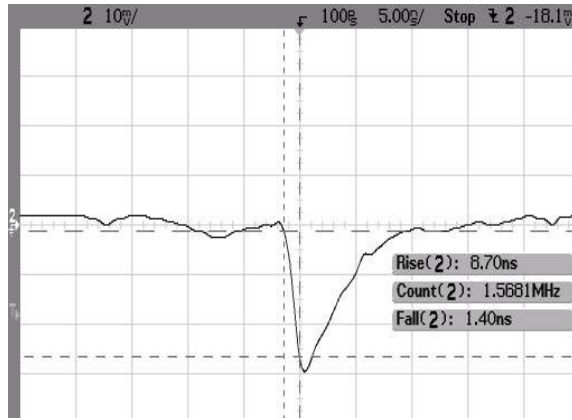


Fig. 5 (a). Single dark count pulse, showing the fast rise and recovery time of the SPM and (b). LED illumination - pulse duration is 100ns with a repetition rate of 1MHz.

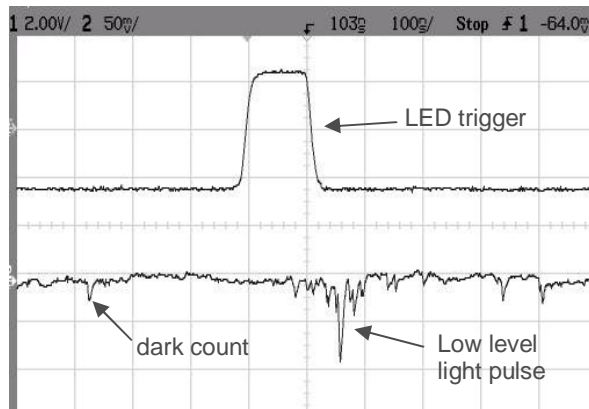


Fig. 5(c) The SPM response showing photon structure for low light intensities & dark counts.

2.3 Single Photoelectron Spectrum

As discussed in the previous section, each GAPD cell that comprises the SPM detector is sensitive to single photons and produces a large signal with noise limited. Noise is limited to the single photon level. If the charge from each pulse of light is integrated and measured, the light spectrum is obtained. This is achieved by using a charge integrating ADC module, the gate signal for which is produced using the trigger output of the LED driver. This technique is very sensitive and for low photon numbers the individual photoelectron peaks can be resolved as shown in Figure 6. The spectrum here shows photoelectron peaks up to a value of 3 with a mean number of photons per pulse of 1-2. The fact that the peaks are individually resolved is testament to the low system noise and the uniformity of all the GAPD cells that comprise the SPM. The spectrum in Figure 6 allows a direct measurement of the SPM gain. The separation of the peaks in the spectrum, corrected for the gain of the preamp and the charge scale of the ADC allows the calculation of the amount of charge produced from a single photoelectron. From the spectrum in Figure 6 a gain of 5×10^6 is calculated. The gain is actually dependent on the capacitance of the individual diodes and so increases linearly with bias and area. This linear behaviour is interesting to note against the exponential dependence of the conventional APD on bias.

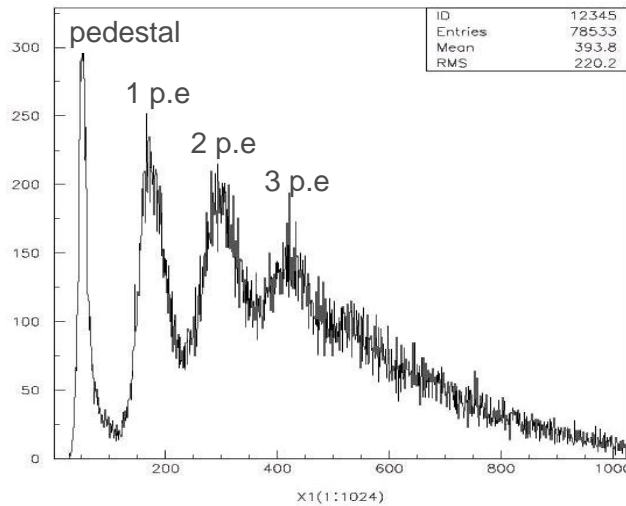


Fig. 6 A charge spectrum showing the peaks corresponding to (from the left) pedestal (noise), single photoelectron peak, 2 photoelectron peak, 3 photoelectron peak.

2.4 Quantum efficiency of single pixels

It should be noted that photon detection efficiency (PDE) of the SPM structure is a combination of detector efficiency (QE, avalanche probability) and fill factor. The fill factor is defined as the ratio between the active area of the GAPDs and the total area of the SPM and is determined by the size and geometry of the pixel and its pitch.

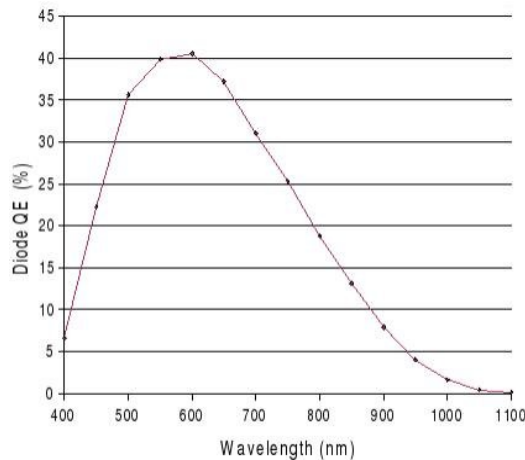


Fig 7 Pixel QE for SPM device

Figure 7 shows the QE of a single SPM pixel. It can be seen that for this device the peak sensitivity is centered on 650nm with a detection efficiency of about 40%. For the SPM device, this quantum efficiency is corrected for the geometrical active area, i.e fill factor. This factor depends upon the exact geometries used, but can reach 50%+. This gives an SPM PDE of 20%, which is comparable with that from a photomultiplier. The following section further addresses the issues affecting the photon detection probability.

2.5 SPM Model

The design of an SPM for a particular application involves the optimization of a number of competing parameters to achieve the highest possible PDE. The measured dark count distribution of singles pixels was used as an input to the simulation activity to model the effect of the total dark counts for the SPM cell. Two major factors in determining the performance of the SPM are the quantum efficiency of the GAPDs and the SPM fill factor. At present, the pixel spacing is limited to about 15µm in order to limit optical crosstalk, although it is possible to reduce this further by optically isolating the pixels from each other using trenches. Figure 8 shows the fill factor and array size (total number of pixels/dynamic range) as a function of pixel size for a square pixel geometry and a pixel spacing of 15µm.

The fill factor can therefore be optimized by tuning the pixel size to give a maximum photon detection efficiency while maintaining a linear response in the range of photon intensities appropriate to the application. A good knowledge of the optical signal is therefore very important in customizing the SPM parameters. However, the response of the SPM to an optical signal is also dependent on a number of other factors including optical pulse shape, pixel dead time, dark rate, pixel crosstalk and GAPD efficiency. To incorporate all these factors and accurately simulate the response of a real SPM, a Monte Carlo (MC) model has been developed.

The model predicts the photon detection efficiency of an SPM from a statistical analysis of the pixels for a given optical pulse and pixel parameters. The block diagram, shown below, details the parameters taken into account when simulating the response of the SPM. The output of the MC simulation can then be used as an input to a circuit simulator to obtain the electrical output from the detector for different readout circuits

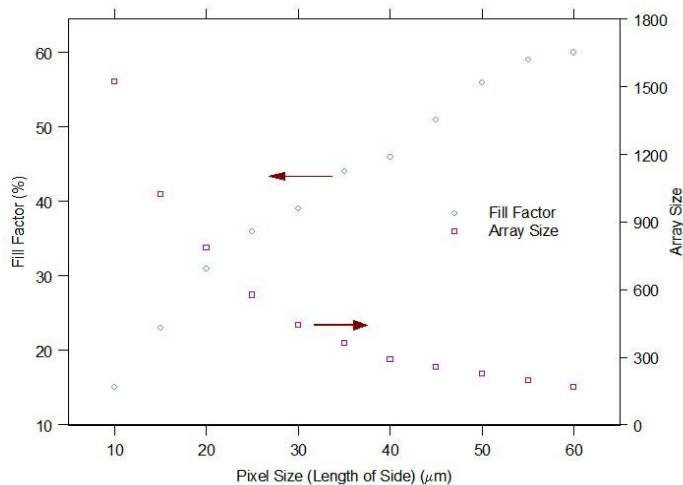


Fig. 8. Fill factor and Array Size (Dynamic Range) as a function of pixel size for a square pixel geometry and a pixel separation of 15µm. The plot shows the trade off between a high fill factor value and the dynamic range for a 1mm² SPM.

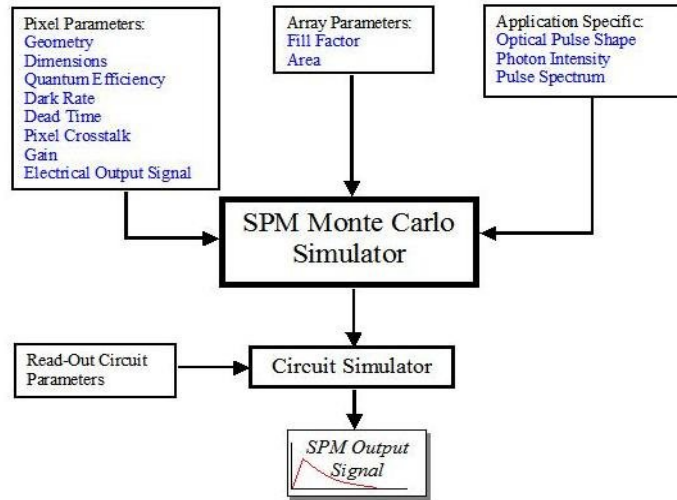


Fig. 9 Block diagram of SPM simulation detailing inputs into the Monte Carlo model and circuit simulator.

Figure 10 shows some typical optimization plots for a 30ns optical pulse containing 1300 photons incident on a 1mm² SPM. The effect of increased pixel quantum efficiency on the optimum pixel size has been shown by plotting the photon detection efficiency as a function of pixel size for three different values of QE.

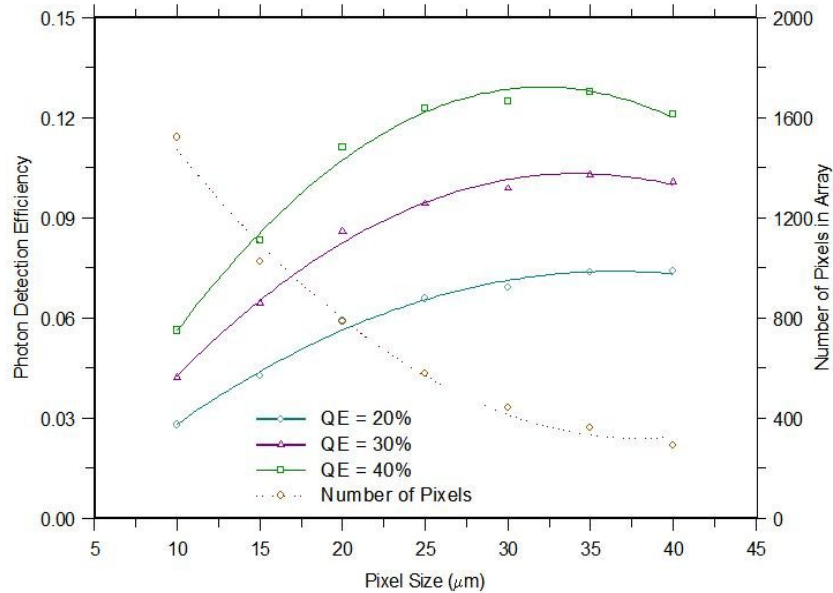


Fig. 10 Optimization of the pixel size for different GAPD Quantum Efficiencies.

The figure shows that the optimum pixel size has a range of <10um (32-40um) for a QE of 20% and that this range narrows and shifts to the left as the QE of the number of GAPDs increases. At small pixel sizes the photon detection efficiency is dominated by the fill factor. As the pixel size increases, the fill factor increases and the photon detection efficiency reaches a maximum. The detection efficiency then saturates and begins to fall as the pixel size and fill factor are increased further due to the reduction in SPM dynamic range. As the quantum efficiency of the APDs are improved the photon detection efficiency of the SPM increases and optimum pixel size reduces to provide the required increase in dynamic range.

Once the pixel size has been optimized for the incident pulse and GAPD parameters, the linearity of the response can be modeled for different intensity pulses. The linearity and dynamic range of three 1mm² SPMs with different pixel sizes are shown in Figure 10. The figure shows the linear response of the SPM and the saturation of the signal when the dynamic range of the device is reached for pixels with a quantum efficiency of 30%.

The above simulations are all based on an SPM area of 1mm². The dynamic range can be increased further by increasing the total SPM area. However, as the SPM area increases the pixel size must also increase to maintain the fill factor. Since the dark rate is proportional to pixel area, the trade off between pixel area and dark rate becomes the deciding factor. Figure 11 is a simulated response of a 1mm² SPM with three different pixel sizes as a function of pulse intensity.

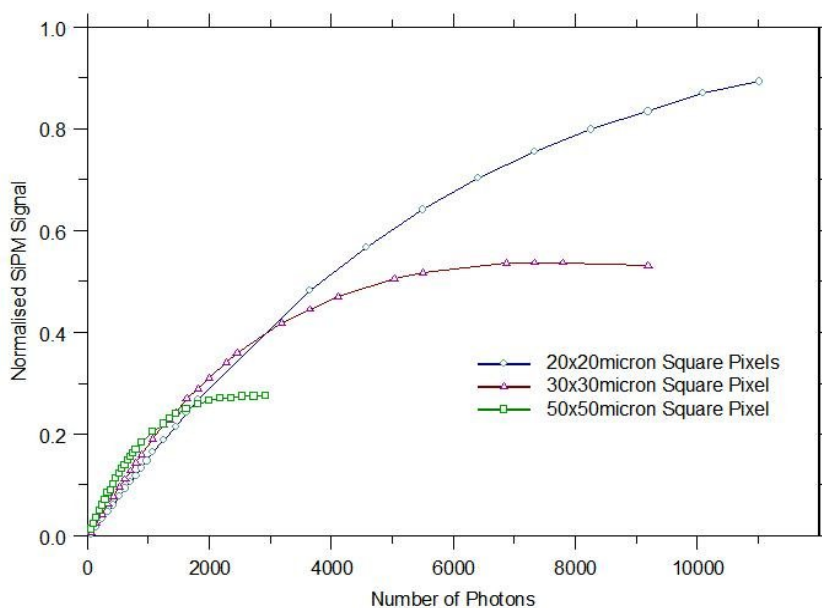


Figure 11. Simulated response of a 1mm² SPM with three different pixel sizes as a function of pulse intensity.

3. CONCLUSION

The SensL SPM reported here in many ways reproduces the performance of a traditional vacuum tube PMT. PMTs are still the de-facto standard for many light sensing applications but have practical limitations associated with their fragility, bulk, high bias voltage operation and sensitivity to magnetics. The SPM represents a detector that competes on performance, as well as overcoming the shortfalls of PMT technology mentioned previously. Experimental results for 1mm² SPM structures have highlighted the high gain (5×10^6), low bias ($\approx 50V$) operations of the device as well as low dark rates (<1.8MHz) at room temperature, fast rise (1ns) and recovery time (10ns) and good PDE (20%).

The SPM has also been shown here to be a versatile detector whose design can be readily optimized for a specific application or known optical signal. The main trade-offs in the design that should be optimized are the fill factor, determined by the pixel size and SPM area, and the various factors which determine the SPM dynamic range, total number of pixels, QE, dark rate, crosstalk etc. To optimize the design of SPMs, a MC model has been developed to simulate the SPM response to a given optical pulse. The signal from the SPM can then be fed into a circuit simulator to aid the design of the readout electronics and simulate the output signal of the final system. Current developments at SensL are now focused on shifting the peak sensitivity towards lower wavelengths for certain applications and increasing the fill factor of the microcells on each device.

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